THERMOGRAPHY IN THE CONDITION MONITORING OF REFRACTORY LINING

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ABSTRACT

This paper is based on a research project carried out during 1997. The objective was to study how an infrared camera can be used for condition monitoring of converters in the steel industry and the conditions under which thermal scanning can be used to estimate wear of a converter's refractory lining. The objects of the study were the chrome converter of Outokumpu Polarit Oy and the LD-converter (BOF) of Rautaruukki Oy Raahe Steel. The condition of the refractory lining of a converter is presently monitored by periodically measuring the wear of the wall with a laser measuring device during shutdowns or between heats. A breakout of the lining is very costly due to resulting interruptions of the manufacturing process. The study was implemented by carrying out a series of tests at both production plants. Wear of the converters was measured using laser measuring equipment. The surface temperature distribution of the converters was measured simultaneously. The results of the laser measurements and thermal scanning were compared. On the basis of the results of this study, it is possible to increase and intensify the use of thermal scanning in condition monitoring of processes of the steel industry or as a process monitoring instrument. Thermal scanning has the significant advantage over other thickness measuring methods that the process need not be interrupted for measuring. The research project will continue in 1999.

1. INTRODUCTION

Outokumpu Polarit Co

The chrome converter (CRC) process is a part of the stainless steel production chain in the steelmaking process of Outokumpu (figure 1). Figure 2 shows a cross section of the brick lining of the CRC. A 40 mm thick steel shell forms the outermost layer. Inside that is the actual refractory lining. The different layers of the lining from the shell inward are: a 124 mm thick safety lining, a 15 mm thick layer of crushed material for insulation and a 300 - 750 mm thick lining. Dolomite is used as the lining material. The charge weight of a chromium converter is usually between 30 - 100 tons, with the average charge weight at about 65 tons. The life of the CRC lining is about 45 blowings, which is 5 - 6 days in terms of production time. The temperature of the liquid steel in the CRC during one blowing usually varies between 1540 and 1700°C.

The wear profile of the lining is measured using a laser measuring device made by SPVT (Spectra Physics Vision Tech). Quite reliable information is obtained about the thickness of the refractory lining during the various campaign periods. The wear speed and life span prognosis at different points of the lining can be calculated on the basis of these values. During one lining campaign, lining measurements are usually made 2 - 4 times in such a way that the first measurement is made during the first 5 blowings at the beginning of the campaign, and the rest every 15 - 20 blowings until at least 40 blowings have been carried out. One measurement made by one measurer takes about 20 - 30 minutes. The laser measuring device has proved to be an excellent tool when testing different brick qualities and studying the effect of different process variables on lining wear. The measuring density of the measuring device is based on the size of a predefined raster, which is normally 150 mm. When a 150 mm raster is used, measurement information is obtained for at least every other brick. Laser measurements of the lining

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have provided information about the behaviour of the process and the life of different brick qualities under demanding CRC conditions. Thickness measurements do not give information about the penetration of the metal through the joints of the brickwork to the safety lining, which can later initiate a breakout. A breakout of the lining cannot be totally avoided even though its condition is monitored. By using continuous thermal scanning it is possible to anticipate a breakout of the lining in the area suitable for scanning. Moreover, the process need not be interrupted for the period of thermal scanning .

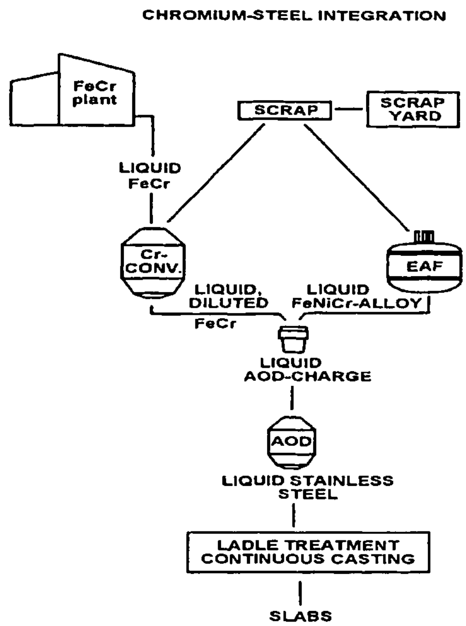

Figure 1. Steelmaking process of Outokumpu Polarit

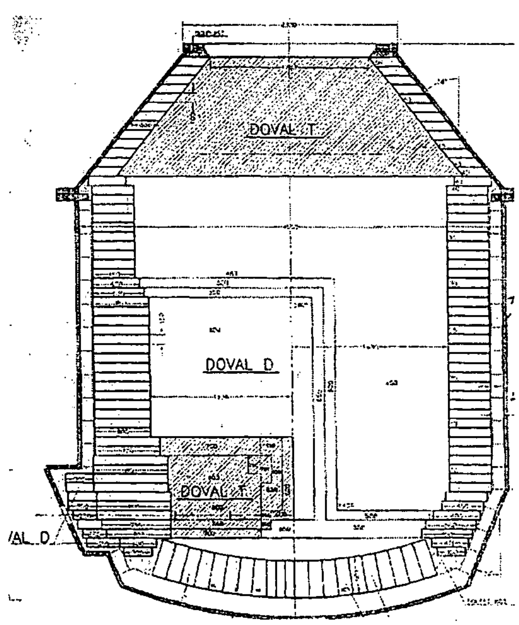

Figure 2. A cross section of the brick lining of the CRC (chrome converter)

Rautaruukki Oy Raahe Steel

Low alloy carbon steels are made at the Rautaruukki steel plant. The steel is refined in three LD converters, two of which are simultaneously in process use while one is shut down for lining. The volume of the converter when new is 87.9 m^3 and the height of the meniscus level of a heat of 120 tons is about 1.6 m. The oxygen blow typically takes 16 minutes. The production of a heat with its various operations takes about 45 minutes. Thus, 30 heats per day are normally produced in one converter. The wearing lining of the converter is currently made only of magnesite bricks. The carbon content of magnesite bricks varies depending on the intensity of wear and the prevailing conditions. The higher the carbon content, the better the slag resistance of the bricks. Earlier dolomite was also used in part of the lining. The thickness of the lining on the wall is 450 - 500 mm, and on the bottom, 900 mm. A safety lining made of magnesia (fosterite) has been laid under the lining.

Converter lining condition monitoring is based on two methods: visual condition monitoring and measuring of wear using a laser measuring device. The condition of the lining and the converter jacket as well as that of the mechanical devices is visually estimated in connection with sampling after every blowing. After the converter is taken into use, in other words, after heating, a model is made of the converter lining using a laser measuring device (Spectra Physics Vision Tech). The measurements made during the campaign are compared to the model. The converter campaign normally takes 1650 heats. During that time the converter is measured about ten times, or more often if necessary. The first measurement is made after about 200 heats. On the basis of the measurement results, necessary action is taken if wear is exceptionally pronounced or the wear area deviates from normal. Measurements are made more often toward the end of the campaign so the maximum life of the lining is reached without the risk of a breakout. Although they are made quickly, measurements cannot be made as often as necessary without restricting production. The need for constant measurement of the lining still exists.

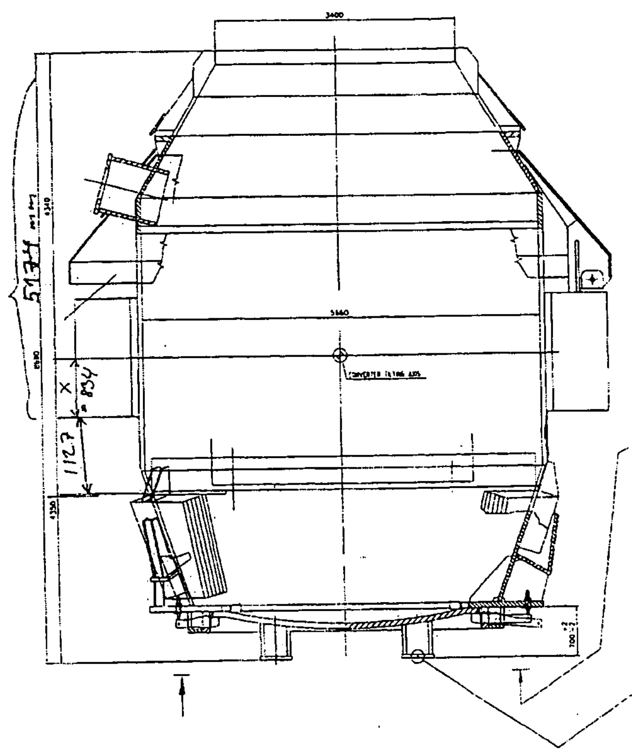

Figure 3. LD-converter (BOF), Rautaruukki Oy Raahe Steel

2. CHROME CONVERTER MEASUREMENTS

A CRC-1 converter was chosen as the object of measurements for the following reasons:

- there are thickness differences in the scanned area (the laser measurements) of the converter lining
- the wear of the converter lining is well known in regard to the blowings
- a considerable part of the surface of the converter can be scanned
- there are no obstacles in the converter structure which hamper scanning
- surface temperature probes supporting the measurements can be installed in the area to be measured
- surface temperatures can be monitored during the process

In practice, it was possible to scan the surface of the converter at two places. The converter was scanned from the lower level and the scanning distance from the converter was about 10.2 m from below. The scans were performed with an Inframetrics 760 infrared camera. The camera operates in the 8 - 12 µm range (long wave range). The results were recorded on VHS videotape and computer diskettes. The scan of the centre line of the area was about 20°, starting from the scanning level. The scanning area was about 2.15 m x 1.65 m. The border of the described area contained steel and slag. The nominal thickness of the brickwork was 400 - 500 mm. Figure 4 shows the scanning target. The scans were performed during two campaigns. The duration of the first campaign was 34 blowings during an 8 day period and that of the second campaign was 40 blowings during four days.

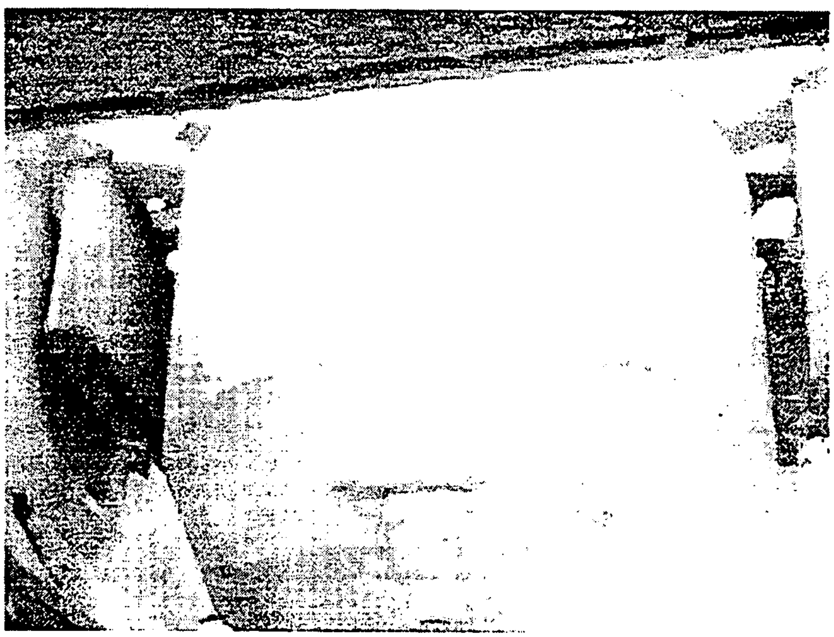

Figure 4. The scanning target (chrome converter)

The average temperatures and maximum temperatures were calculated for 18 separate areas chosen from the area included in the thermal image. The image areas are shown in figure 5. Scans were started when the blowing began and the thermal images were recorded at intervals of about 5 min until the end of the blowing. Depending on the duration, 10 - 20 pictures were recorded during one blowing. Whenever possible, the same temperature scale was used during the scans.

Wall thickness was measured with a laser measuring device before the thermally scanned blowings. The areas corresponding to the areas marked in figure 5 are marked in figure 6.

To study emissivity and as a reference for thermal scanning, FeKo (J-type) thermocouples were installed on the surface of the converter using screws.

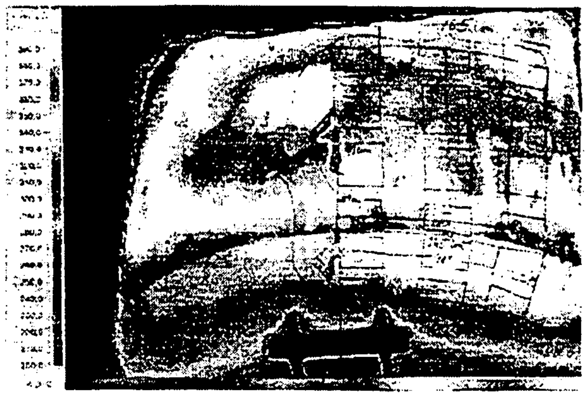

Fig 5. Thermal image, measured areas

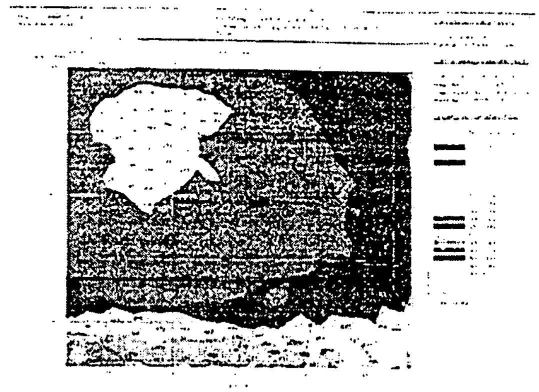

Fig 6. Laser image, measured areas

3. RESULTS OF CHROME CONVERTER MEASUREMENTS

Blowings 4, 14, 23, 30 and 31 were measured during the first campaign. The entire campaign included a total of 34 blowings. Blowings 7, 9, 27, 29 and 31 were measured during the second campaign. The entire campaign included 40 blowings altogether.

The results obtained with an infrared camera during the first campaign were no more than 10 % higher than the results measured using a thermoelement. Emissivity was given the value 0.90. When measurement accuracy is taken into consideration, there was no difference in the values obtained with the infrared camera and the thermoelement during the second campaign. The emissivity value was 0.93.

The surface temperature level of the converter rose about 3°C per blowing in the measured areas during the first campaign and the thickness of the lining decreased appr. 6 - 10 mm. Depending on the area, the surface temperature level rose 76 - 86 °C during the 27th blowing and the wall thickness decreased 172 - 293 mm during the 30th blowing. The surface temperature level of the converter rose about 2 - 3 °C per blowing during the second campaign and the thickness of the lining decreased appr. 5 - 13 mm in the measured areas. The surface temperature level rose 50 - 70 °C during the 27th blowing and the wall thickness changed 94 - 289 mm during the same time. However, no rise in the surface temperature of the converter walls could be detected during single blowings. The highest measured average surface temperature was 370 °C, but the maximum temperature detected in the image area of the infrared camera by the end of the campaign was about 400 °C.

We were able to scan the chromium converter over a relatively large area. There was a definite correlation between wall thickness and surface temperature. The lining of the chromium converter wore relatively linearly, depending on the number of blowings. The surface temperature rose as the lining got thinner. Production conditions also affected the amount of change in the surface temperature: the structures cooled during shutdowns, so the change in temperature during the campaign is not rectilinear.

The initial situation of the campaign is shown in figure 7 (laser measurement) and 8 (thermal image), and the final situation in figures 9 and 10.

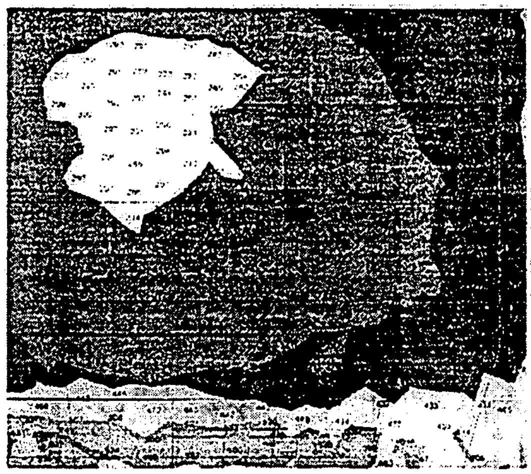

Figure 7. Initial situation, laser measurement

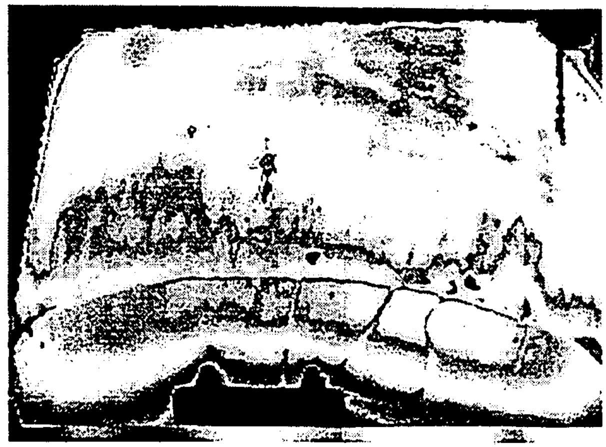

Figure 8. Initial situation, thermal image (200-300 °C)

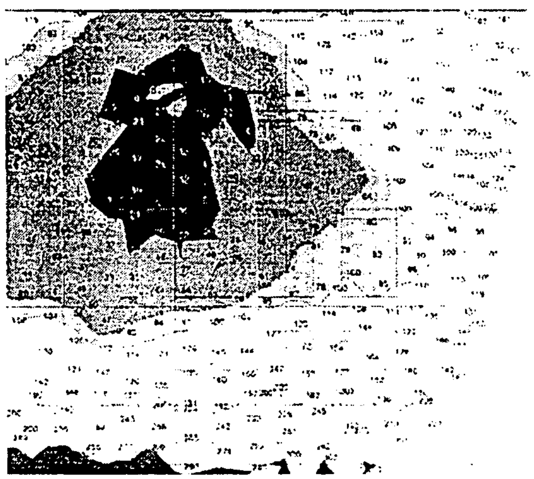

Figure 9. Final situation, laser measurement

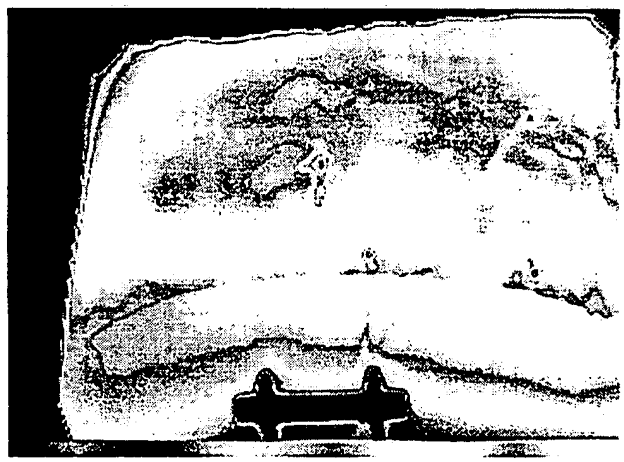

Figure 10. Final situation, thermal image (200-400 °C)

Figure 11 shows the dependency between the surface temperature and wall thickness of all the areas measured during the first campaign. Figure 12a and 12b shows the surface temperatures and wall thicknesses of measured areas 1.1 - 1.6 during the first campaign. Deviations in surface temperatures are caused by 24 hour shutdowns between blowings, during which times the structures cooled. Figures 13, 14, 15 and 16 show the initial and final situations of the second campaign. The temperature scale of the thermal images in figure 14 is 250 - 300 °C and in figure 16, 300 - 400 °C.

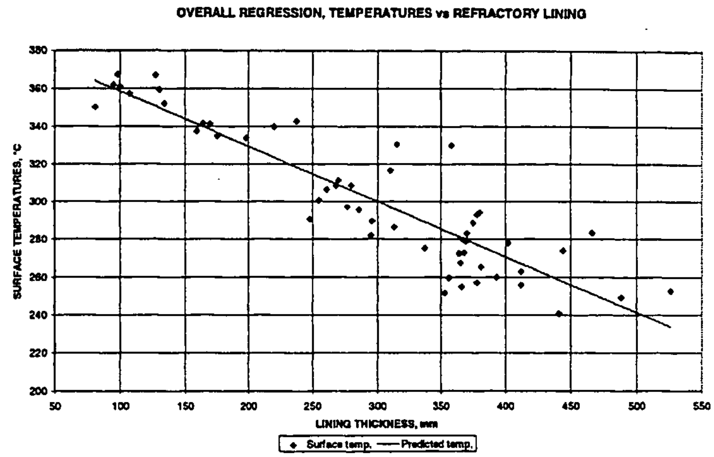

Fig. 11. Surface temperatures and wall thicknesses during the first campaign

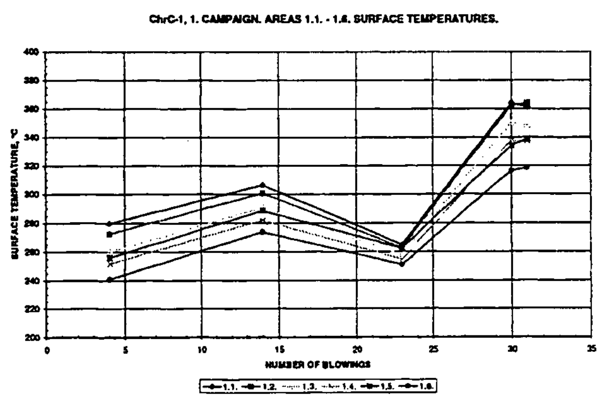

Figure 12a. Surface temperatures of areas 1.1-1.6.

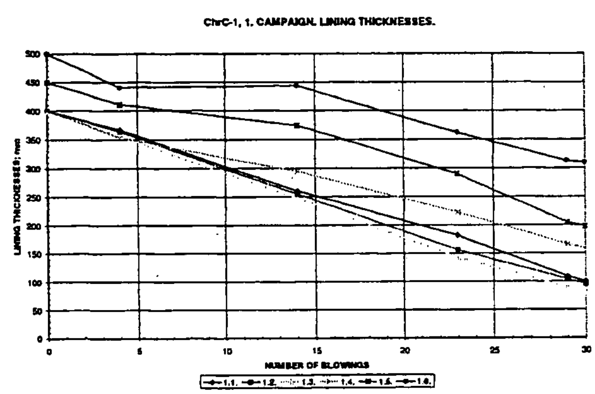

Figure 12b. Wall thicknesses of areas 1.1-1.6.

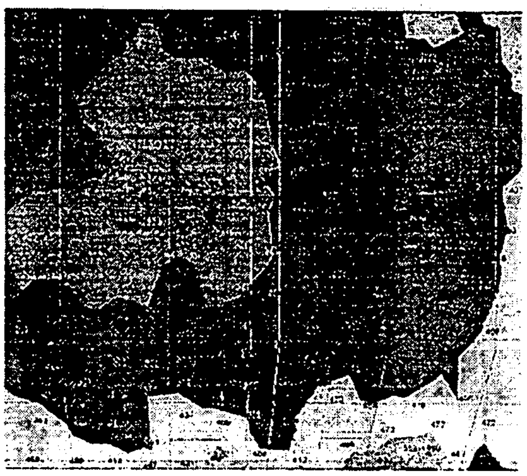
Figure 13. Initial situation, laser measurements

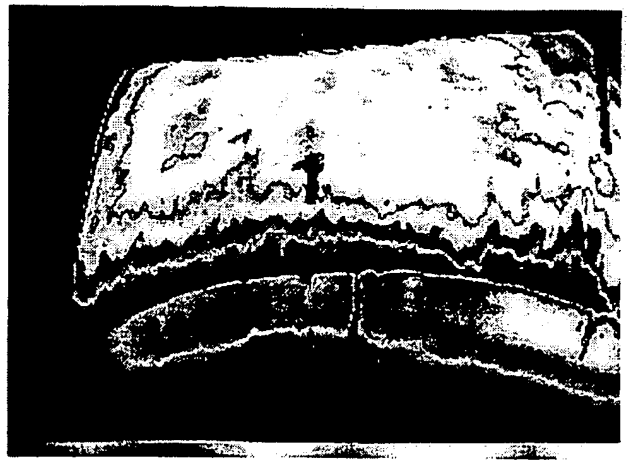
Figure 14. Thermal image, scale: 250 - 300 °C

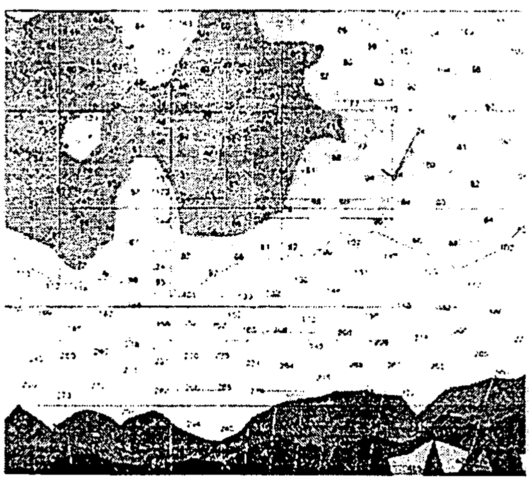
Figure 15. Final situation, laser measurements

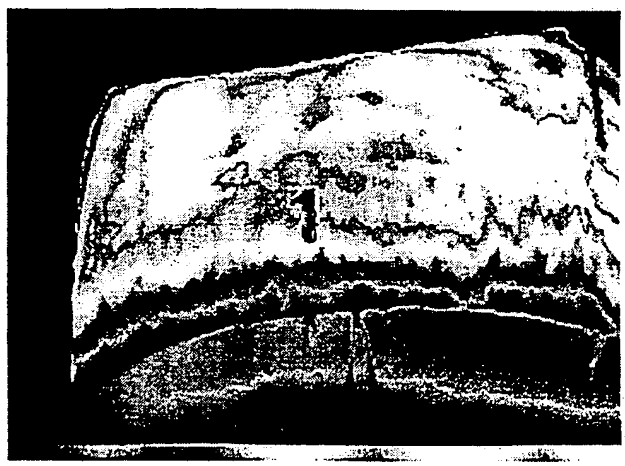
Figure 16. Thermal image, scale: 300 - 400 °C

Figures 17 and 18 show the surface temperatures and corresponding wall thicknesses of areas 1.1 - 1.6 during the second campaign.

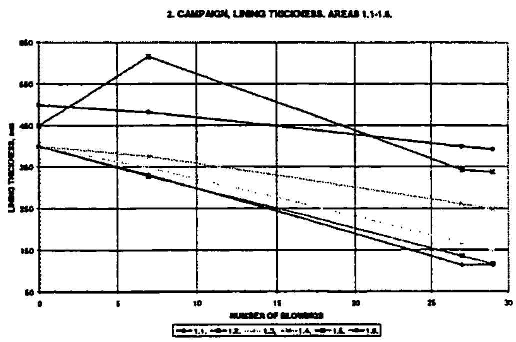

Figure 17. Wall thicknesses (2nd campaign)

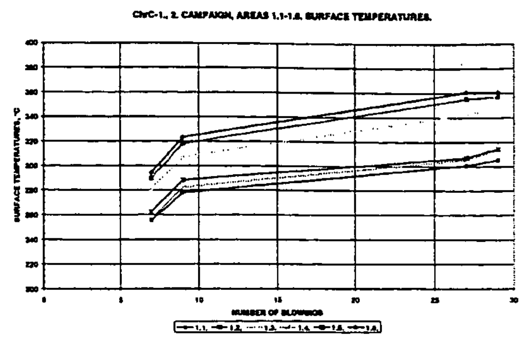

Figure 18. Surface temperatures (2nd campaign).

Figure 19 shows the correlation between the measured surface temperatures and wall thicknesses during the second campaign.

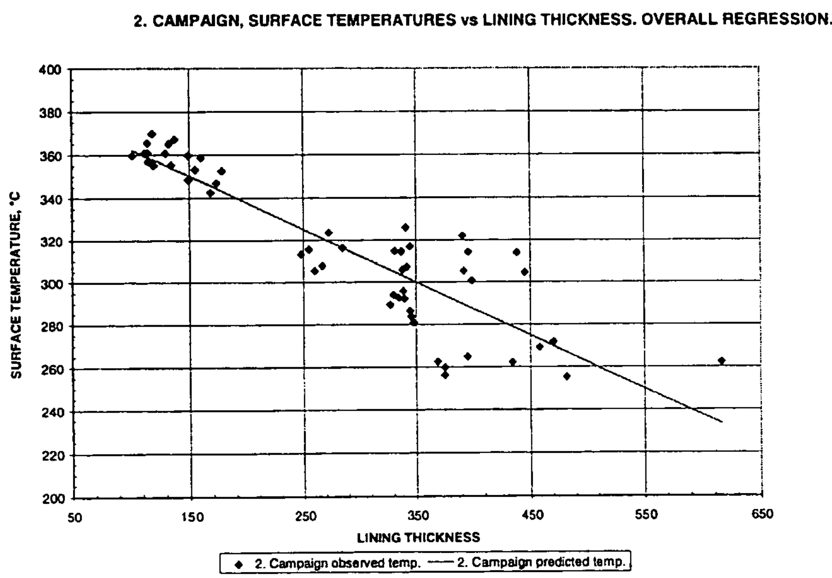

Figure 19. Second campaign, overall regression

4. LD CONVERTER MEASUREMENTS

The converter nr. 1 was chosen as an object of measurement due to the fact that a new campaign was beginning. It was possible to scan the surface of the converter from three different directions. For practical reasons the scans were made from the lower level from the tapping side. The most problematic areas of the converter were not visible. Besides, the back of the converter is in the zone which is slagged (sculling), in other words, the wall thickness varies. The scanned area are shown in figure 20.

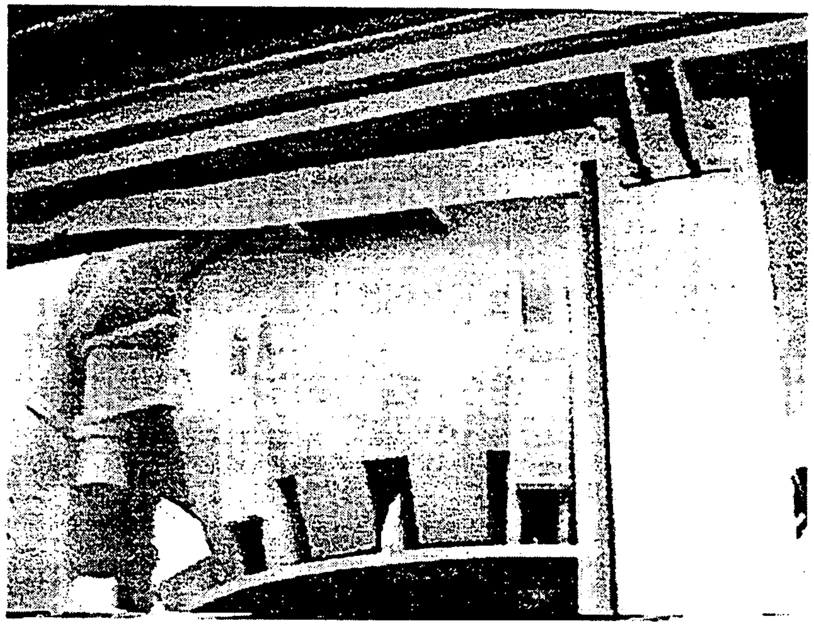

Figure 20. The scanned area, LD-converter (BOF)

The scans were performed with the same Inframetrics 760 infrared camera. The results were recorded on VHS videotape and computer diskettes. The duration of the campaign was 1300 heats during 48 days. The average temperatures and the maximum temperatures were calculated for 5 separate areas chosen from the area of the thermal image. The areas are shown in figure 21. Scanning started at the beginning of the heat and the thermal images were recorded at intervals of about 5 min. until the end the heat. Scans were usually not recorded in the middle of the heat because of splashes, and there was about a 10 min break. About 5 - 10 scans were recorded during one blowing. The size of the area to be examined was about 3.25 m x 1.15 m. The measuring distance was about 8 m and the viewing angle about 20°.

Wall thicknesses were measured with a laser during the campaign. The laser measurements were made at separate times, not in conjunction with the thermal scans. Reference measurements by means of contact temperature measurements were not made during this campaign. Figure 22 shows the areas corresponding to the areas marked in figure 21.

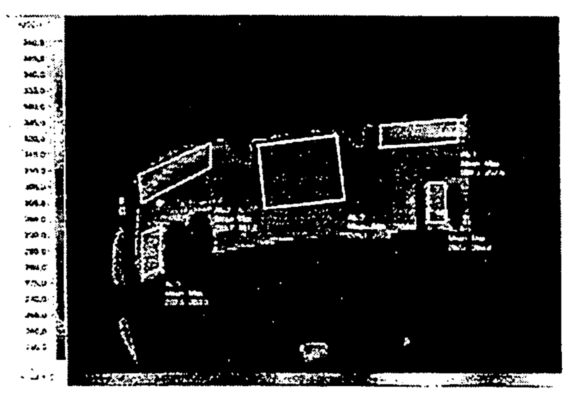

Fig 21. Measured areas, thermal image

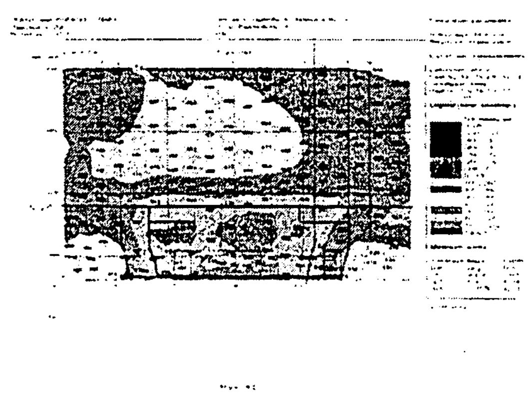

Fig 22. Measured areas, laser image

5. RESULTS OF LD CONVERTER (BOF) MEASUREMENTS

The thickness of the walls in the examined area varied because of slagging. Correlation between surface temperature and wall thickness was difficult to determine because the laser measurements and thermal scans were performed at different times. Overall wall thicknesses of the areas examined during the campaign varied from 582 mm to 806 mm and the surface temperature fluctuated between 226 and 326 °C. Surface temperatures of about 440 °C were measured on the other side of the converter when the campaign ended.

Based on the measurements, there is a correlation between surface temperature and wall thickness, but since

- surface temperature and wall thickness measurements could not be made simultaneously for technical reasons and
- the measured thickness of the converter wall varied due to slagging
- there is a possibility of error in defining wall thickness because it is based on a CAD model (not the actual structure)

a reliable correlation between the measurement results can not be calculated.

The variation in wall thickness as such should not pose a problem as long as no significant changes occur in the thermal conductivity of the structure.

Near the end of the campaign a surface temperature of over 440 °C was measured from between the protective rings at the front of the converter while the surface temperatures of the measured areas varied from 250 to 330 °C. At the end of the campaign the lining had worn the most at the front of the converter. The hottest measured areas were at the upper edge of areas A 1 and A 2.

With the current arrangements, the protective structures of the converter prevented us from using the thermal camera to scan the most interesting areas from the standpoint of wear.

Thermal scanning and laser measurements should be performed simultaneously. It should be possible to make better use of the results of thermal scanning by implementing thermal conductance models. The measurement results obtained now will be used to test the solution procedure presented in the following chapter.

The surface temperatures of the measured areas varied about 2 - 5 °C during separate smeltings. Depending on the process conditions, 5 - 10 thermal images were recorded during each smelting. The temperature differences were affected by factors not dependent on the camera, such as smoke, splashes, other external factors and camera location (because of the prevailing conditions, now and then the camera had to be moved to a shielded place), which may have caused slight deviations in focusing, which again affect accurate alignment of the measured area defined on the basis of the thermal image with the help of an image processing application.

6. THE USE OF HEAT-TRANSFER MODELS WITH THE RESULTS OF THERMAL SCANNING

Method of solution

In numerical solution the solution method of heat transfer equation (difference method, integral equation method) is combined with optimization method, in which the thickness of the lining is fitted to an overdetermined boundary condition, which has been obtained in thermal scanning measurements.

In order to simplify the problem, it is supposed that the converter wall consist on homogenious material. If the wall thickness L(t) is known at time instant, thus boundary value problem

$$\begin{aligned}
\frac{\partial u}{\partial t} - a\frac{\partial^2 u}{\partial x^2} &= 0, \ 0 \le x \le L(t), \ t \ge 0 \\
u(x,0) &= u_0(x) \\
a\frac{\partial u}{\partial n}(0,t) &= \epsilon\sigma(u(0,t)^4 - u_\infty(t)^4) \\
u(L(t),t) &= u_s(t)
\end{aligned}$$

is unicly solvable and the solution can be determined by solving the non-linear Volterra integral equation. In other words we have solution operator $T : C([0,T]) \rightarrow C^{2,1}([0, L_0]x[0,T])$ so that the function

$$u(x,t) = T(L(t))(x)$$

is the solution for boundary value problem for every continuous function L(t) describing the wall thickness. By using overdetermined boundary condition on the exterior surface we have another integral equation

$$T(L(t)(0) = u_p(t)$$

in which $u_p(t)$ is the measured surface temperature, the thickness can be determined.

As a solution method are applied well-known integral equation solution methods. Because the solution operator T is a compact operator, the solution method is a mathematically ill-posed problem. If the measurement interferences are too wide or inprecise, the error tolerance will increase too much. These problems can be dealt with by applying e.g. Tichonov's regularisation method or some other known filtering method of measurement signal. This treatise is based on constant heat conductivity, in practice heat conductivity will change by the time, which has to be considered in further studies. Table 1 shows the predicted (pred.) wall thickness values applying the heat transfer model presented above compared wth the values observed (obs.) during the campaign 2 (Chrome converter).

Table 1. The observed and predicted wall thicknesses (Campaign 2)

Blowing	1.1.		1.2.		1.3.		1.4.	
	Pred.(mm)	Obs.(mm)	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.
7	330	330	341	327	369	348	379	375
9	255		266		292		293	
27	118	113	125	135	176	168	249	260
29	119	115	123	116	168	149	233	248
	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.
Blowing	2.1.		2.2.		2.3.		2.4.	
7	330	330	340	340	366	345	374	369
9	255		265		289		290	
27	117	133	123	149	172	178	244	285
29	117	115	122	130	164	160	228	273
	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.
Blowing	3.1.		3.2.		3.3.		3.4.	
7	333	335	323	339	359	346	364	375
9	284		266		294		296	
27	125	120	111	138	170	173	242	267
29	120	102	109	119	162	155	226	255

The wall thickness given by the model differs from those measured at the beginning of the campaign ± 5 % and in the the end appr. ± 15 % (the deviation increases).

7. CONCLUSIONS

On the basis of the results obtained in this study, it is possible to increase and intensify the use of thermal scanning in condition monitoring of processes of the steel industry or as a process monitoring instrument. In order to be able to utilise the results of thermal scanning as efficiently as possible, it is necessary to determine the process conditions, such as process energy balances and heat transfer and other factors affecting the measurement results. With an infrared camera today it is possible to achieve a 100 000 point surface temperature distribution with an accuracy of 0.1 °C continuously. A significant advantage of thermal scanning compared to other thickness measuring methods is that the process need not be interrupted for measuring. By improving heat-transfer models it is possible to predict the wearing of converter lining.

7. ACKNOWLEDGEMENTS

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